# 3 e-textiles

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## 3.1 Introduction

The effective incorporation of electric components on fibrous substrates constitutes an important research effort, aiming in the development of textile products with increased functionalities. The development of wearable electronic products has been successfully achieved in the past, at least in terms of functionality. The vision now lies in the fulfillment of the textile prerequisites such as washability, flexibility, comfort as well as acceptable aesthetics. Under these premises, research is now focused on the development of fully textile products with electronic functions, the so-called electronic textiles or e-textiles. Emphasis is thus given in the fibrous structure, which is now called to play an active role in the introduced electrical properties of the end product.

To produce an e-textile product, different technical components, unknown till now to the textile technologists, has to be used. Sensors, actuators, microprocessors, energy sources and the appropriate software are some of the elements that may be used to ensure efficient functionality of the end product. The internal communication of these components be guaranteed by the interfaces, ranging from conventional cables to conductive textiles and/or optical fibres. The external communication, on the other hand, is normally achieved by wireless technology, assisted by the presence of textiles antennas.

The transition from the development of wearable electronics to e-textile products has been reinforced by the increasing research effort in the field of conductive polymers. The fascinating world of conjugated polymers with conductive properties opens new routes in polymer and textile technology. Indeed, traditional insulators as textile fibres can now be modified and transformed into electric conductors.

The dynamic potentials of e-textiles in a future of clothing with integrated electronic properties, gain the attention of the research community, opening a discussion about the variety of the application fields of these innovative materials. Garments for military applications, wearable systems for telemedicine care as well as clothing with impressive aesthetic effects and improved functionalities can change the idea of traditional clothing, improving essentially peoples' quality of life.

This chapter provides an overview of the recent developments and the problems associated with these, in the field of e-textiles. Since the difficulties in e-textiles' study lies in their interdisciplinary nature, this chapter also hopes to provide some insight in their basic scientific disciplines, which can bring a future of personal assistant garments a step closer.

## 3.2 Electric conductivity-Background

Electric current expresses the flow or the interaction of a materials' free electrons. Actually when a voltage is applied from an energy source, an electric field is developed. This electric field forces the positively charged particles as well as the free electrons of the materials' chemical structure, to flow. The subsequent inability of the positively charged particles to move, results from their engagement into covalent bonds. Therefore, the free electron carriers are forced into an oriented flow, which is called electric current. The nature of electricity is best understood through the examination of the chemical structure of matter. It is thus known that matter is composed of atoms, consisted of electrons, protons and neutrons. The positively charged protons, as well as the uncharged neutrons, are in association and they are the elements that constitute the atoms' nucleus. The negatively charged electrons appear as cloud around the nucleus, orbiting in predetermined shells. Although oversimplified, Figure 3.1 shows a typical representation of the electron motion.

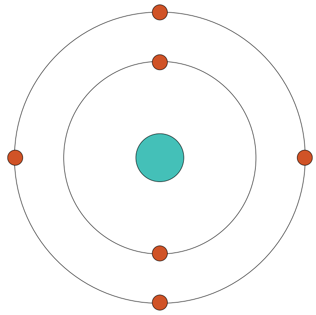

**Figure 3.1**: Electron's orbits around the atom's nucleus.

An extensive description of the quantum theory is beyond the scope of this chapter. However, it is of high value to refer to its general principles. Based on the above considerations, the energy of each orbiting electron depends on the combined effect of the specific shell properties as well as the possible interactions of the electron with other electrons and can thus be in a predetermined field of (energy) leves/states. Atoms interactions to form bonds would include the subsequent interaction of the free electrons' located in the outermost shell. In solids, things are more complex since a great number of atoms are bonded, forming crystalline solid materials. The independent atoms free electrons' can be located in many energy levels, depending on their chemical interaction with the surrounding atoms. The possible energy levels of the free electrons led to the development of the energy bands. The band corresponding to the outermost shell is called valence band. As expected and depending on the atom, the valence band can be fully occupied by electrons. On top of the valence band is the conduction band. The two bands are divided by a gap, called forbidden band, the size of which will determine the materials' electrical nature. The above theoretical consideration results in the categorization of materials according to their molecular structure. According to the aforementioned classifications, materials are divided into insulators, semi-conductors and conductors. Insulators in terms of band theory, have their valence band fully filled, leading to an inexistence of their atom structure's free electron and to a large forbidden band. The energy needed to promote electrons from the valence band to the energy band is large enough to be supplied by a weak electric field or by electrons' thermal vibration. On the other hand, in typical conductors such as metals, the size of the gap is small or non-existent, allowing free electrons to be easily promoted to the conduction band. Additionally, metals valence band is not filled, which also allows to the free electrons to easily "travel" from the valence band to the conduction band. In semiconductors, valence band is fully filled but the size of the forbidden gap is small enough for the free electrons to be promoted to the conduction band, at least at room temperature. The electrons vibration energy, a quantity highly depended on the temperature, would define the electrical behavior of semiconductors.

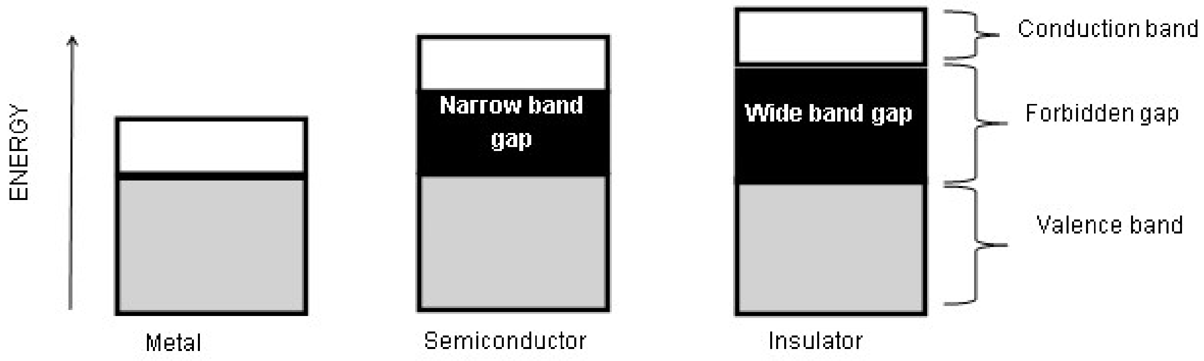


**Figure 3.2**: The band structure of a metal, a semiconductor and insulator (Wallace et al. 2009, p. 119).

The relation between the current flow through a conductor and the applied voltage is mathematically described by Ohm's law, one empirical and the most fundamental law in the study of the electric circuits.

$$I = \frac{V}{R} \tag{3.1}$$

where R is the electrical resistance measured in Ohms (Ω), V is the voltage applied across the conductor measured in Volts and I is the electric current which flow through the conductor, measured in Amperes.

The effect of the material's geometry in the material's electric behavior can be determined by a mathematical expression:

$$\rho = R\frac{A}{L} \tag{3.2}$$

where ρ is the resistivity measured in (Ω cm), l is the length of the sample and A is the sample's cross section.

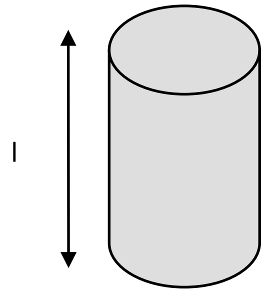


**Figure 3.3**: Geometrical representation of a fibre structure (Warner 1995, p. 253).

Electrical conductivity (σ), expressed in S $m^{-1}$, expresses the ability of the material to conduct the electric current and is the reciprocal of resistivity, ρ:

$$\sigma = \frac{1}{\rho} \tag{3.3}$$

The electrical conductivity depends on the carriers' flow as expressed in the corresponding mathematical equation.

$$\sigma = nq\mu \tag{3.4}$$

where n is the number of charge carriers, q is the carrier's charge and μ is the carriers' mobility.

| Material | Resistivity (Ω m) |
|---|---|
| Superconductors | $<10^{-25}$ |
| Metal Conductors | $\sim10^{-8}$ |
| Semi-Conductors | $10^{-4}$-$10^{-10}$ |
| Insulators | $10^{10}$-$10^{20}$ |

**Table 3.1**: Typical resistivity values for superconductors, metal conductors, semiconductors and insulators (Harlin 2006, p. 217).

1. The reciprocal of Resistance (R-1) is called conductance and is measured in Siemens (S) S=Ω-1.

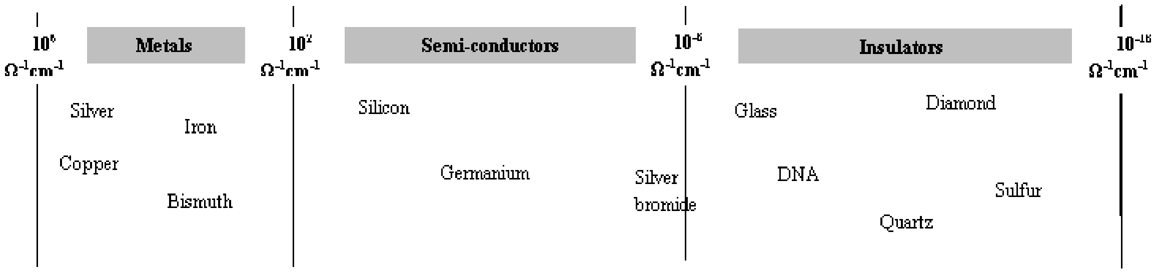


**Figure 3.4**: Comparison chart of conductivities in $Scm^{-1}$ for conductive polymers, compared with metals, semi-conductors and conductors (Ghosh 2006, p. 239).

## 3.3 Conductive textiles

Our interest materials, textile fibers behave typically as electric insulators. This is because the chemical structure of polymers does not contain free electrons that would act as carriers to produce electric current upon application of an electric field. According to numerous studies (Kim et al. 2004; Dall' Acqua et al. 2004; Micusık et al. 2007; Knittel 2009) conductivity in textiles can be introduced via:

- Filling of fibres with carbon black or production of carbon fibres
- Interlacing in the textile structure metal , steel, or nickel wires or fibres
- Coating of textiles (fibres or fabrics) with conductive substances
- Modification of the polymer structure through the effective incorporation in the textile structure of intrinsically conductive polymers (ICP)

The superior conductivities of fabrics containing metal fibres are overwhelmed by the reduced flexibility, the increased weight, the cutting and processing problems as well as the increased cost of the end product. Additionally, the aesthetic priorities of textile products weaken the carbon filling method. Coating of textile substrates with metal salts usually reduces the wash resistance of the end product. Metallic and galvanic coatings have been also used, with limited success though (Meoli 2002; Tang 2006).

Intrinsically conductive polymers (ICP) were for a long time an unfulfilled dream of polymer scientists. Intense research interest has resulted to the successful development of polymers with acceptable conductivities and thus to a Nobel Prize in Chemistry in 2000. Scientists have concluded that the key for the development of conductive polymer lay in their conjugated structure, meaning the presence of alternative single and double bonds in the polymeric backbone. Polyaniline (PANI), polypyrole (Ppyr), polythiophene, poly(p-phenylene sulfide) as well as their derivatives are some of the most representative examples of conductive polymers. A critical evaluation of the relevant literature reveals that the unprecedented high levels of conductivities achieved by the aforementioned polymers; do not line with the limited environmental stability and the processability issues that they present. Polymeric chain conjugation introduces a degree of stiffness in the material's structure, which impedes the polymer's solubilization (Harlin 2006). Furthermore, an electro-conductive polymeric structure is normally susceptible to oxidation and to possible acid attacks which can lead either to the complete polymer degradation, or to the disruption of the conjugated structure (Das et al. 2010).

The reality of the ICSs synthesis is though to be correlated with the vision of the development of effective conductive textiles. Furthermore, while the development of ICPs with improved properties is at the center of the scientific research, ICPs effective application on textiles has also been the subject of a large number of studies (Kuhn et al. 1993; Lin et al. 2005; Micusık et al. 2007; Wu et al. 2009), ICPs can be applied in textiles substrates in the spinning dope, offering thus ICSs a "host body" with acceptable mechanical properties (Kaynak 2005; Harlin 2006). Another route that is steadily gaining ground is the development of conductive polymer coatings that can be easily applied on the fibre's or fabric's surface. Coating may provide solution in terms of the manufacture process, offer though doubtful durability of the desired conductive properties. Conductivity can be also introduced in textiles by conductive inks. Developments in digital printing are also beneficial, making printing with conductive inks possible. The undoubtful benefit of this method is the possibility of electrical circuits printing on conventional textiles (Tang 2006).

A competitive relation does exist between the innovative electro-conductive properties and the traditional textile properties as comfort, flexibility, durability, washability etc. Further research is defenitely needed in order to further explore this new class of materials and improve their properties. However, the commercialization of conductive polymers introduce textiles in a futuristic digital future, forcing them to rediscover their potentials.

## 3.4 Textile sensors and actuators

The electric signals' transmission in an e-textile system is assured by the use of conductive textiles. actually conductive threads replace the circuits' interfaces such as wires, offering increased comfort to the wearer. Technological advances have also led to the effective incorporation in the systems of electric components, which can transform the transmitted signals. It is known that the transformation of electric signals is possible due to two different electronic elements: sensors and actuators. Sensors are devices which transform physical phenomena such as light, intensity, sound, temperature etc., into a physical quantity – usually electric signals. On the other hand, actuators consists a components' category with the opposite functions, meaning the transformation of electrical signal into physical parameters. The transformation of one energy form to another is called transduction. The simplest wearable garment consists of conventional sensors and actuators connected with wires to power sources, all embedded in a textile substrate. A demand for functional wearable systems with textile properties moves the scientist interest in the development of electronic building blocks such as sensors and actuators compatible with textile priorities. Although progress in sensor technology minimized the size of sensors, it did not contribute a lot in the enhancement of their flexibility. Taking as granted the scientific principles in sensor technology, the interdisciplinary research in the field of e-textiles challenges the sensors' raw materials. The development of conductive polymers pushes forward the dynamics of this endeavor, making flexible sensors a reality.

Strain textile sensors have been developed from conductive coated textiles. Electrical conductance can be related to the conductor's geometry, according to the mathematical expression of Ohm's law (see equation 2). Fibres' extension between their elasticity limits, results in the material's cross-section reduction and in a consequently increase in its resistance (Langenhove et al. 2007, p. 106). A critical factor in the development of textile sensor is the fabric geometry as fibres' arrangement in a textile structure affects the structure's conductivity. Furthermore, problems associated with the response time and the durability of the developed products have been noticed, suggesting that further research is needed.

Textile pressure sensors are another scientific effort that has gained intense scientific interest. Various mechanisms are used to assure the soft sensor's functionality (Catrysse et al. 2004). A straightforward approach would consist of two layers of conductive fabric separated by a non-conductive mesh. An introduced pressure would allow the conductive layers' contact and the flow of the electric current, as illustrated in Figure 5. Alternative constructions based on the same scientific principles have also been developed, leading to the production of commercial products such as the "SoftSwitch", the "sensory jacket", the "Gorix" and others (Cho 2009, p. 582).

| Application | Information Processing |
|---|---|
| Weighing Scales | Gravity-pressure-weight |
| Switch | Touch pressure-threshold-on/off |
| Respirometer | Respiration-chest volume-clothing pressure-respiratory rate |
| Gesture measurement | Acceleration by movement- dynamic gesture Changes of body surface-piezoresistive change-dynamic/static gesture |
| Accelerometer, vibroscope | Pressure change by inertia-acceleration/vibration |

**Table 3.2**: Application and information processing of a pressure sensor (Jeong 2010, p. 89).

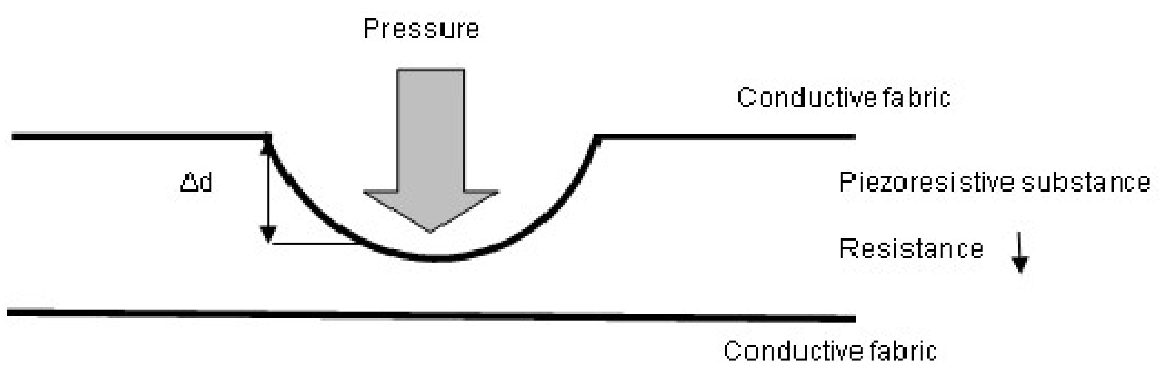


**Figure 3.5**: Principles of piezoresistive sensor (Jeong 2010, p. 89).

Special mention deserves the development of textile electrodes for electrocardiogram (ECG) (Langenhove et al. 2007, p. 106; Jeong 2010, p. 89). Although textile electrodes offer improved comfort to the wearer, increasing the recording duration compared with conventional electrodes, they still produced signals with increased noise. “Textrodes”, which are commercial available textile electrodes, consist of stainless steel fibres embedded in a belt. the belt is designed to be worn around the thorax (Catrysse & Puers 2007, p. 88).

Sensors make an electric circuit capable of “sense”. The interpretation of the “senses” is assured by systems capable of delivering the “senses”, such as actuators. It is thus obvious that sensors abilities should not be considered independent in a circuit, or treated as isolated building blocks of a system, but rather as electrical elements interrelated with other circuits’ transductions. A medical garment with temperature sensors, for example, provides information regarding the levels of skin temperature. The subsequent transformation of the produced results into a physical action by the addition of an actuating device, such as a display, would maximize the circuit performance. In a more sophisticated version of the same product, the garment can incorporate a thermochromic function “programmed” to trigger when the skin temperature level exceeds a predetermined value.

Actuators that can be used in an e-textile system are textile displays, electroactive polymers as well as color-changing materials. Electric stimulation triggers electroactive or color-changing materials, which respond with the appropriate property change. Textile displays are more complex structures. Nevertheless, France Telecom has already developed a textile display using optical fibres.

The addition of sensors and actuators in an e-textile system push wearable technology in a different level. Improvements are needed but the route has been opened, making scientists dreaming of soft washable electric circuits.

## 3.5 Power supply sources for e-textiles

The operation of the electronic components described above (sensors, actuators, conductive textiles) presupposes the continuous provision of energy in the form of electrical power. Batteries – normally AAA or button – is the most widely used energy source, although they are bulky, heavy and with limited lifetime. The demand for e-textiles, which can provide comfort as well as functionality, led to the development of alternative power supply technologies or minimization of the size of the existing options. Lithium and rechargeable batteries can be considered as the most obvious option in this direction. Progress has also been noticed in the development of flexible batteries. Nevertheless organic photovoltaics, solar panels and other energy harvesting devices have been also considered as vital alternatives to conventional portable power sources. The vision now lies in the development of close energy e-textile systems, that can provide energy generated from the human body movement or temperature (Gho 2009; Min 2010, p. 214).

## 3.6 Processors/ Microprocessors

The data provided by the input devices, such as sensors are guided to a Central Processing Unit (CPU) which basically consist the brain of the system. Analysis of the data is performed by the CPU, which sends the new data to the output devices, such as actuators. Although the CPU has been minimized and sewable CPU has been commercialized, it is worth noticing the textile processors are not yet available.

## 3.7 Communication technologies in e-textiles

Communication of the different components of an e-textile product is essential for the functionality of system. Additionally, the information provided by the incorporated sensors and actuators have to be analyzed and communicated to the interest party. Three areas of analysis exist, as demonstrated in Figure 6: Personal Communications Networks (PCN), Wide Area Networks (WAN) and Information Systems (IS) (Lam 2009, p. 215). In a more straightforward categorization, the communication requirements can be internal (short-range communication) and external (long-range communication). Internal communication is normally assured by wired systems. In addition to conventional wires, conductive and optical fibres have been used, increasing the product's flexibility and thus comfort. Communication of the received data outside of the product is also possible with conventional wires but wireless technology is preferred due to the incomparable benefit they offer in terms of usability. It is obvious that wireless technology opens the potentials of e-textiles systems, especially for medical applications. The most frequent wireless technologies used in the field of e-textiles include IR (infrared), Bluetooth, Wi-Fi, GSM (Global System for Mobile Communications), GPRS (General Packer Radio Service), UMTS (Universal Mobile Telecommunications Systems) etc (Rantanen 2005, p. 198; Tang 2006; Cho 2009; Lam 2009, p. 205; Seymour 2009, p. 12; Seymour 2010, p. 10).

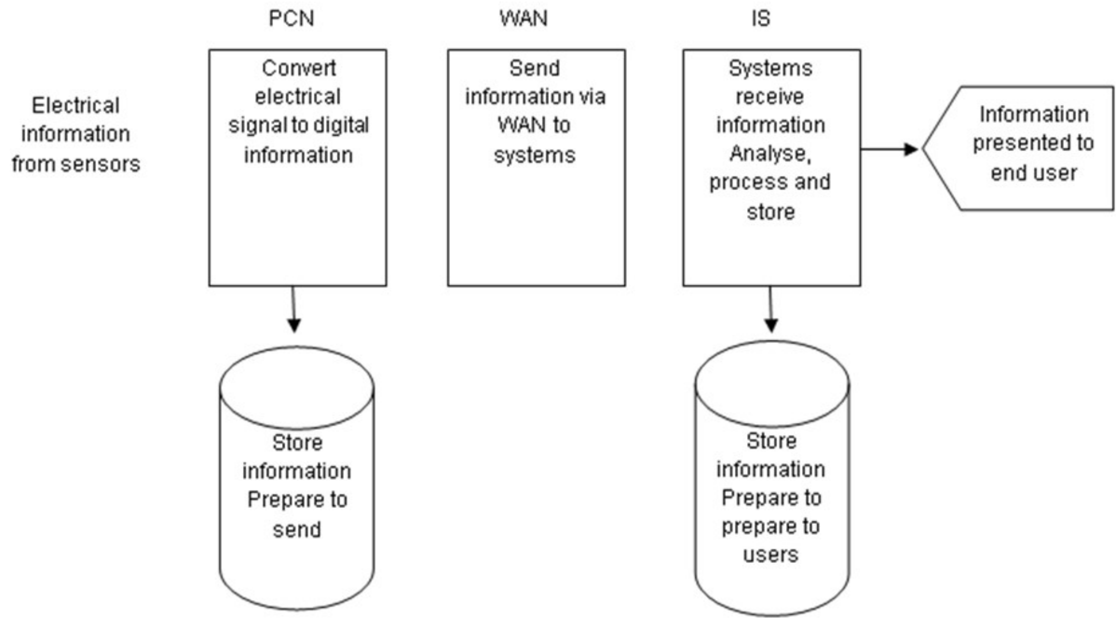


**Figure 3.6:** End-to-end process flow (Lam 2009, p. 205).

## 3.8 Conclusions

An overview of the main building blocks of an e-textile system was presented in the current chapter. The basic scientific principles of textile conduciveness are explained to give to the student a comprehensive fundamental understanding of these innovative structures. The difficulty of the current chapter is routed in the interdisciplinary nature of e-textiles. Innovations in this area do not derive from structural textile modifications textile modifications, rather than from a revolutionary re-appreciation of existent electronic technologies. A detailed investigation of the electronic technologies is beyond the scope of this chapter, however the reader can refer to the literature for a more in-depth study of the subject.

The effort is textile oriented and presents the preliminary research effort to introduce superior electronic functions to textiles. E-textiles systems were –till recently- made of conventional electronics embedded into a textile substrate. Progress in textile technology guided by the market demand for comfort textiles, showed that the realization of a fully e-textile structure is possible. However, the difficulties in the mass production of these systems and the increase in cost of the end-products cannot overrule the fascinating potentials of e-textiles, especially in sectors such as medicine, where they can use to significantly improve peoples' quality of life. The early steps in this endeavor moves e-textiles into a visionary cyber world.

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